Week 2-12

Thin Film Transistors 3

Self-assembled monolayers

Threshold voltage drift

Applications

Chapter 8.6.1, 8.7-8.9

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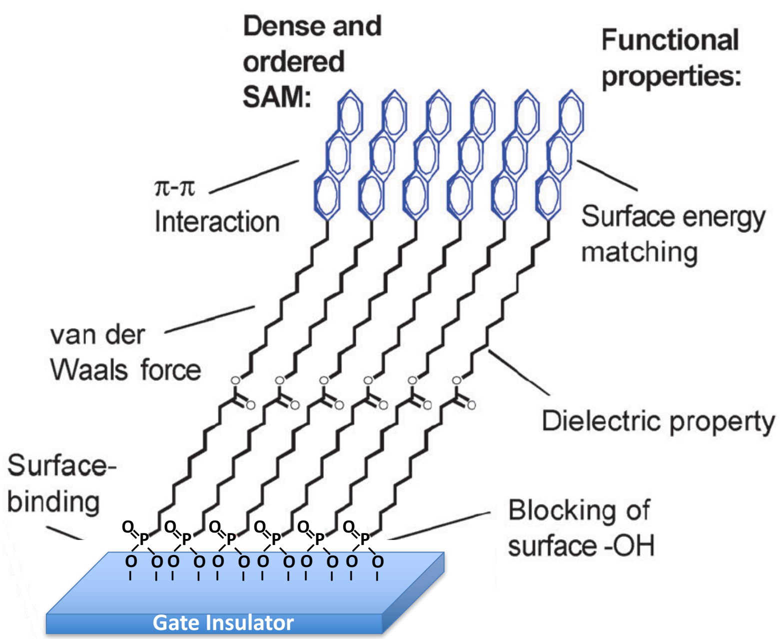
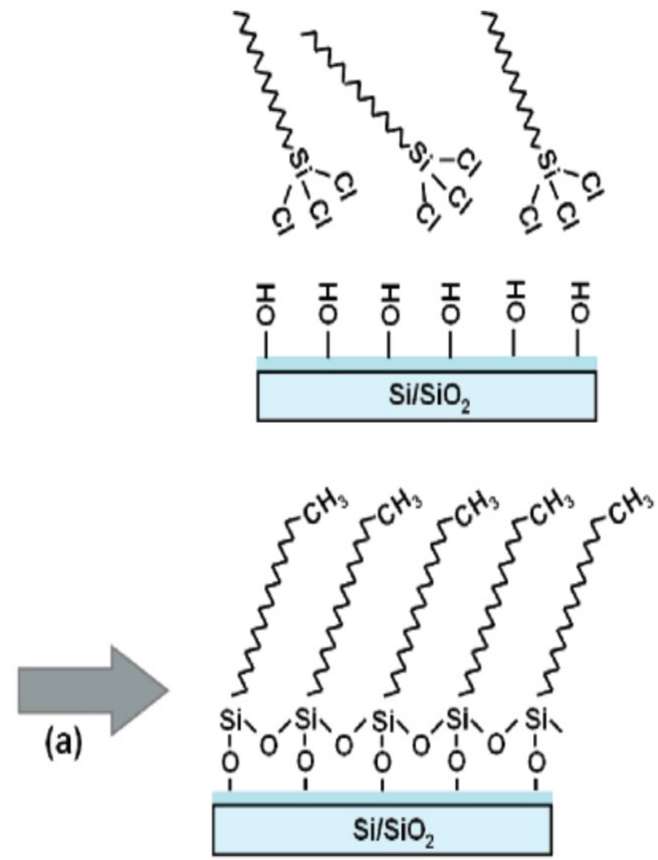
Achieving Optimal Morphologies

- Method 1: Control during growth by VTE, OVPD, solution
- Method 2: Use Self Assembled Monolayer (SAM) functionalization to initiate growth of desired structures by vapor or solution deposition





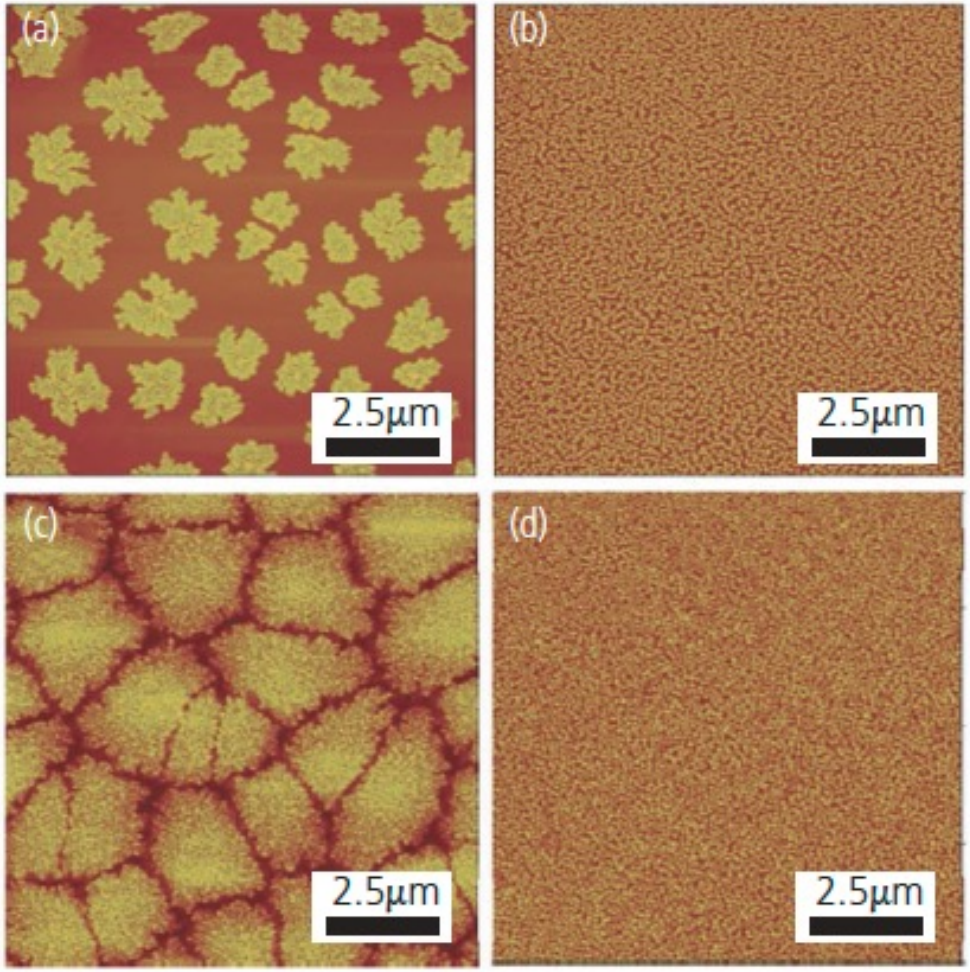
Example: Octyltrichlorosilane (OTS)

Very Different Film Morphologies Achieved Depending on Surface Preparation

Organic semiconductor: VTE deposited C_{60}

ML thick C_{60} on ODPA on HfO_2

ML thick C_{60} on HfO_2



50 nm C_{60} on ODPA on HfO_2

50 nm C_{60} on HfO_2

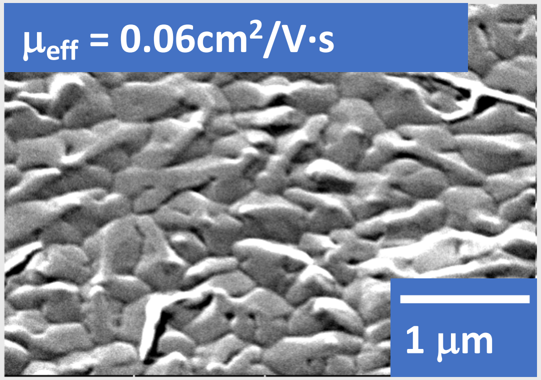
Larger grains on SAMs due to improved molecular surface mobility⇒clustering

Acton et al., Appl. Phys. Lett. 93, 311 (2008)

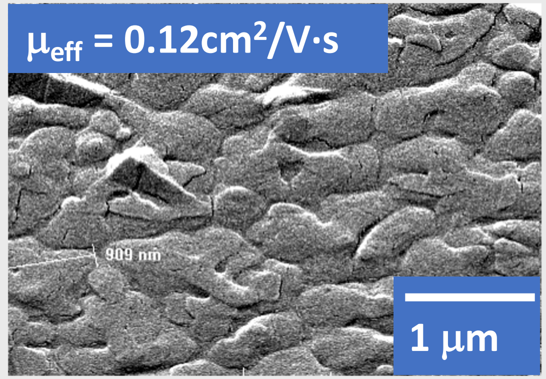
Controlling Pentacene Channel Morphology

OVPD growth

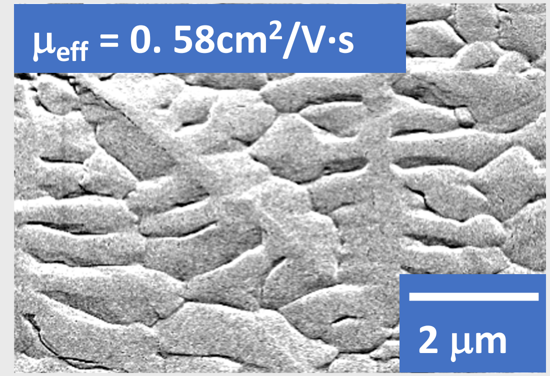
Pentacene on SiO_2



10° C, 0.25 Torr, 3.0 Å/s

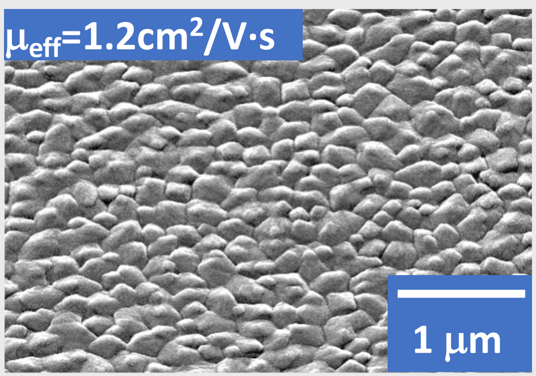


40° C, 6.0 Torr, 1.0 Å/s

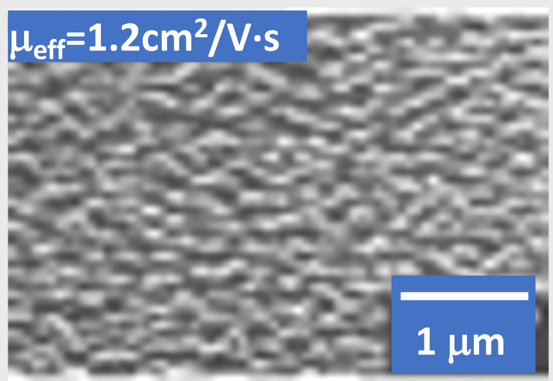


65° C, 10.5 Torr, 0.3 Å/s

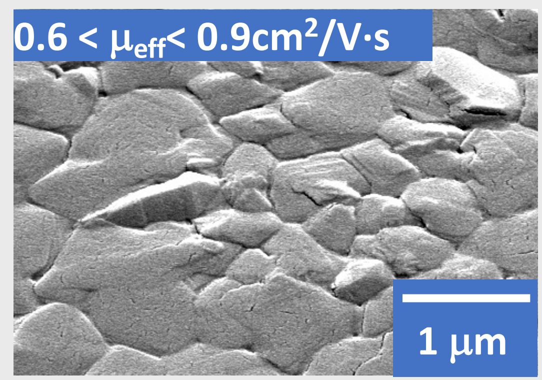
Pentacene on OTS-SAM treated SiO_2



10° C, 0.25 Torr, 3.0 Å/s



40° C, 6.0 Torr, 1.0 Å/s

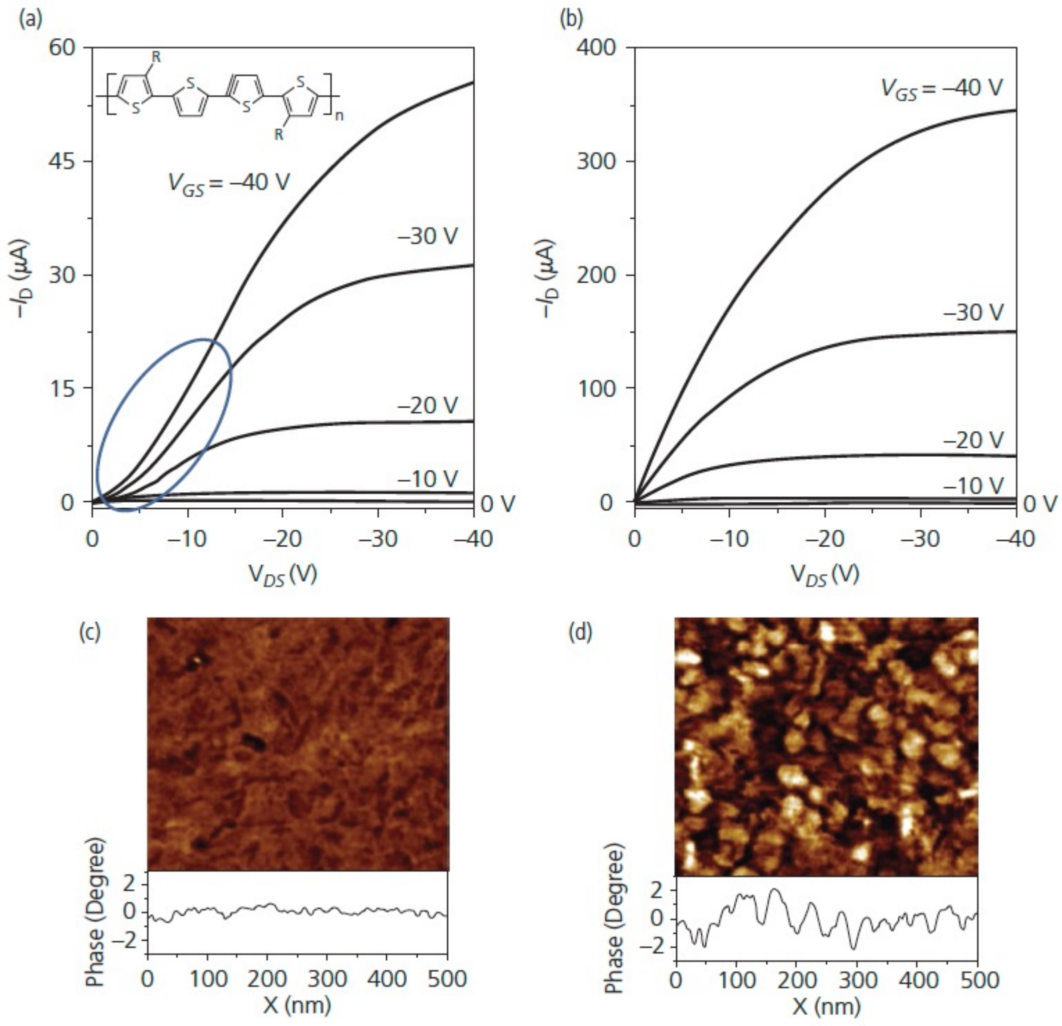


65° C, 10.5 Torr, 0.3 Å/s

toward equilibrium

Functionalizing Metal Surfaces Can Reduce Contact Resistance

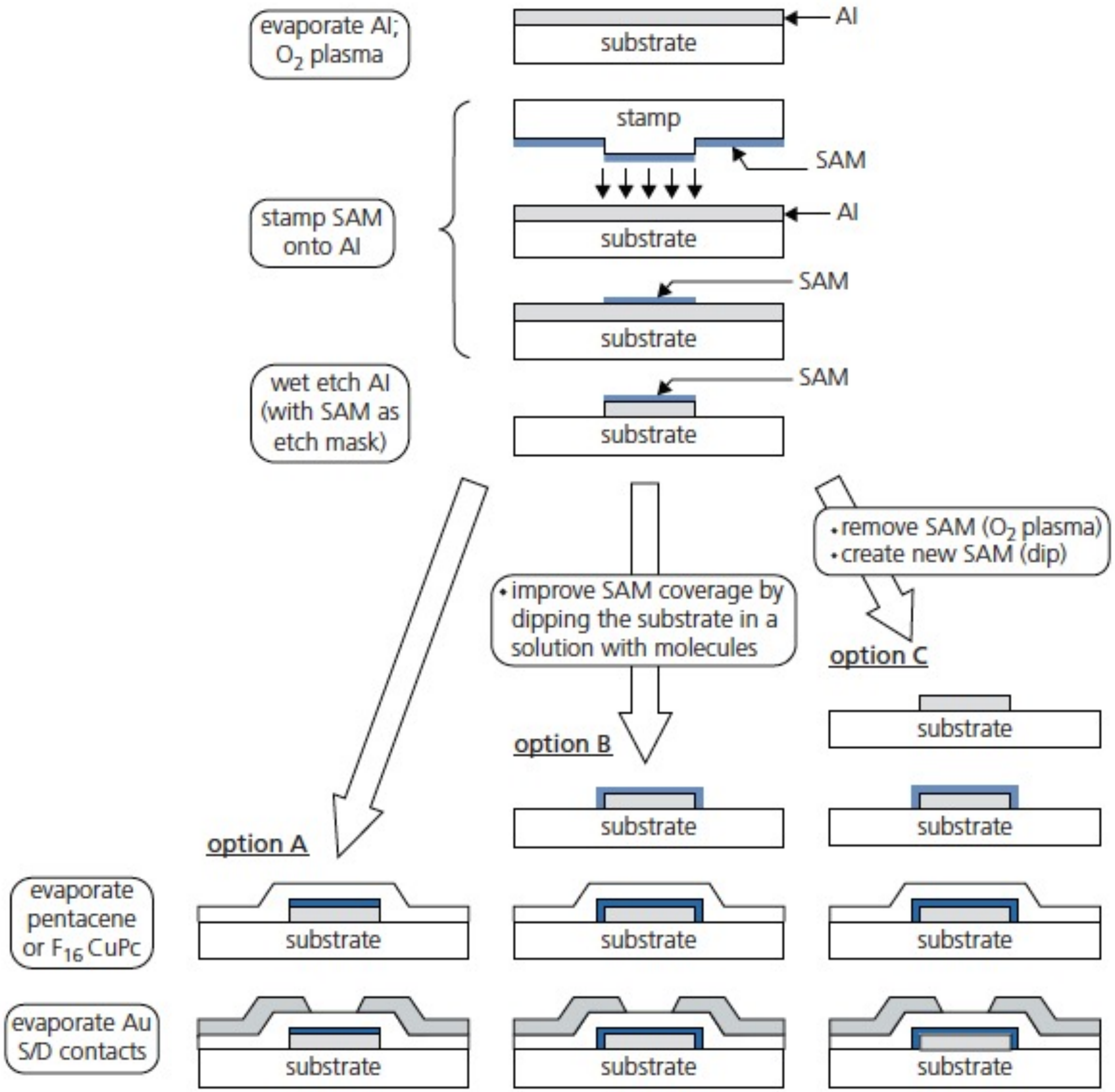
- Alkane thiols stick to Au via S-Au bond
- Alkane anchors subsequently deposited organic channel



Large series resistance (oval region) in untreated substrate (left)
Crystalline grains form on treated substrate (right) with lower R_C

Cai et al., Langmuir, 24, 11889 (2008)

Contact Printing Initiated by SAM

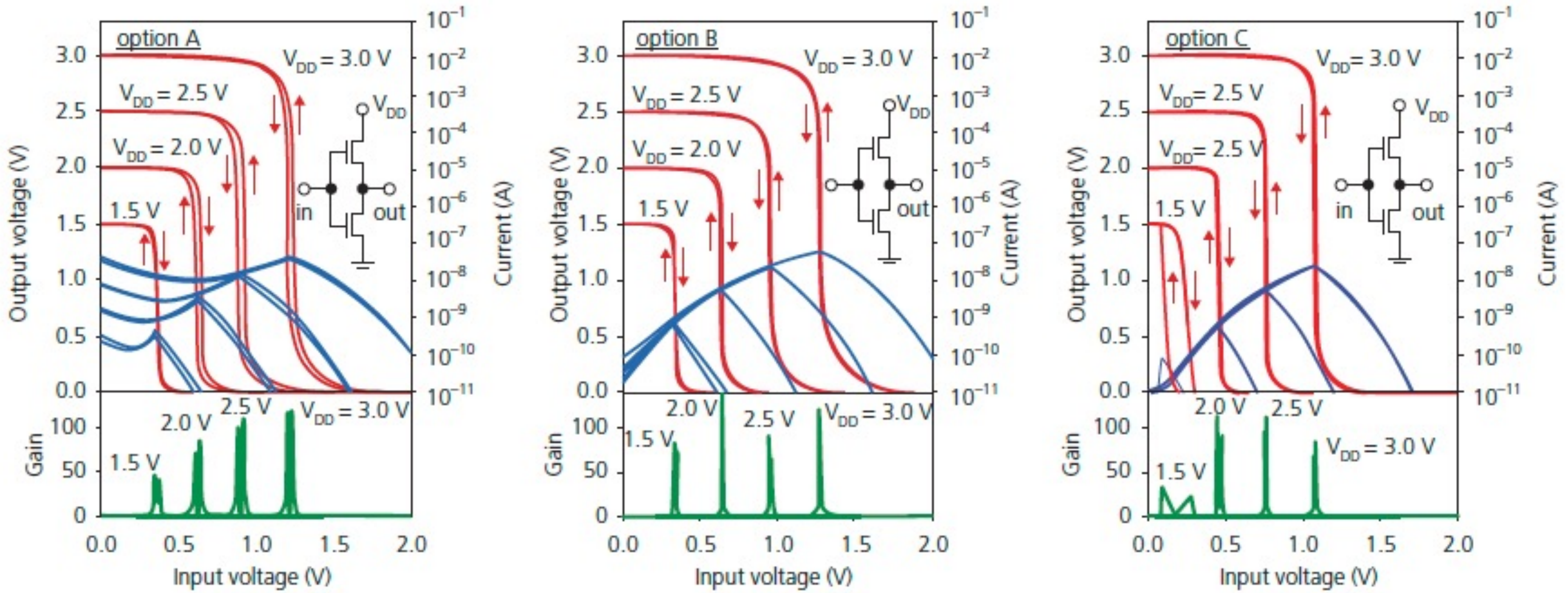


Zschieschang, et al., 2008. *Langmuir,* 24 1665.

Results vs. Deposition Process

Pentacene (p)
$F_{16}CuPc$ (n)

Increasing Device Yield



Operating characteristics not strongly dependent on process

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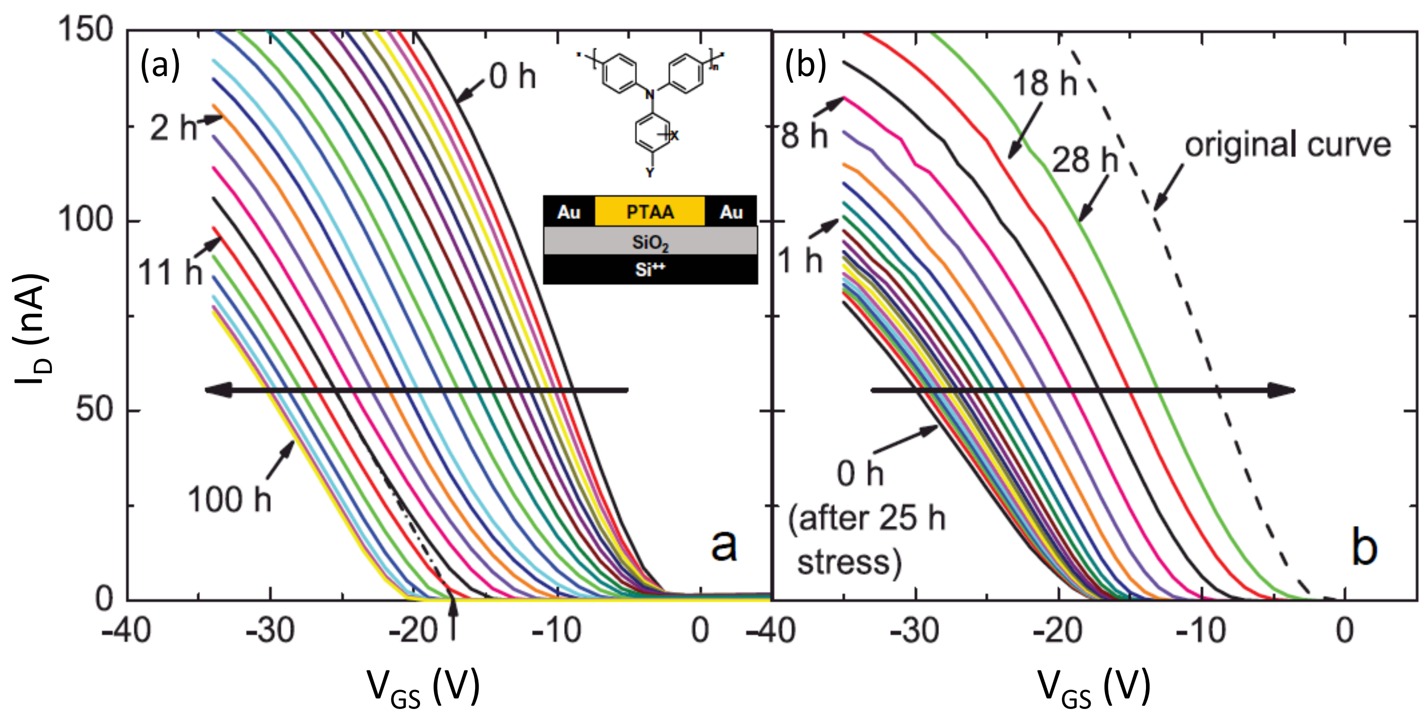
Zschieschang, et al., 2008. *Langmuir,* 24 1665.

Reliability

- Threshold voltage drift the primary source of circuit failure
  - Decreasing noise margin
  - Increasing leakage



Drift $\begin{cases} V_{DS} = -3V \\ V_{GS} = -20V \end{cases}$ Recovery

Original transfer characteristics (and V_T) partially recovered following stress

Sharma, et al. Phys. Rev. B, 82 075322 (2010).

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Threshold voltage drift over time

(see Ch. 6.7 & 7.8)

- Drift due to charges migrating in insulator or channel toward the interface
  - Surface traps at the channel
  - Traps within the semiconductor bulk
  - Charge (ions) drifting within the insulator

$$\Delta V_T(t) = \Delta V_T(\infty)\left(1 - \exp\left(-\frac{t}{\tau}\right)^m\right)$$

Empirical voltage drift expression: Stretched exponential

m = T/T_0 for exponential trap distribution given by:

$$h_{tr}(E) = h_{tr0}\exp\left(-E/E_T\right)$$

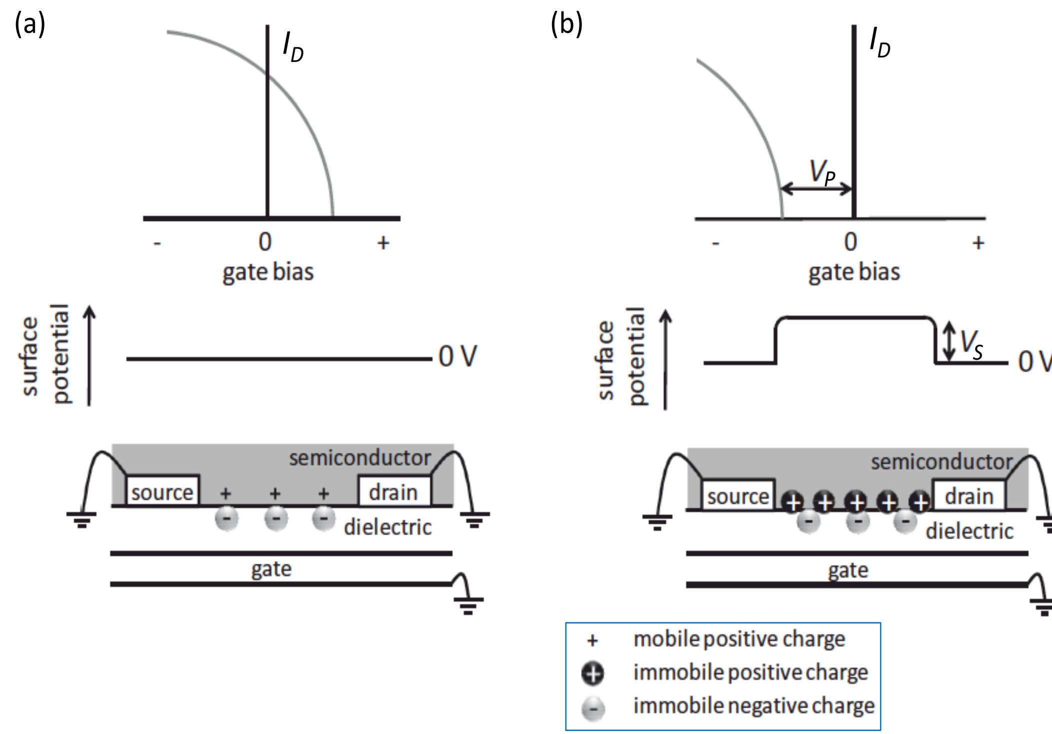
⇒ Time constant for drift

$$\tau = (2\pi v)^{-1}\exp\left(E_T/k_BT\right)$$

Drift occurs over an extended time, and is thermally activated

Water/Proton Generation Drift Model

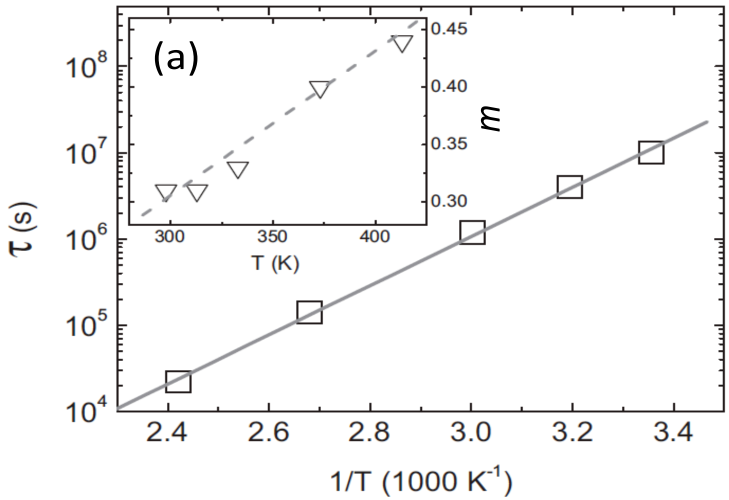
$$2H_2O \leftrightarrow 4H^+ + O_2 + 4e^-$$

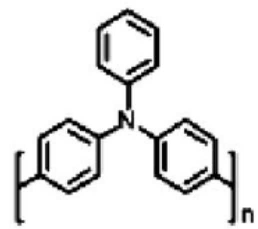


Protons at insulator interface shift the threshold voltage

Mathijessen et al., Adv. Mater. 22, 5105 (2010)

Comparing Proton Model to ΔV_T

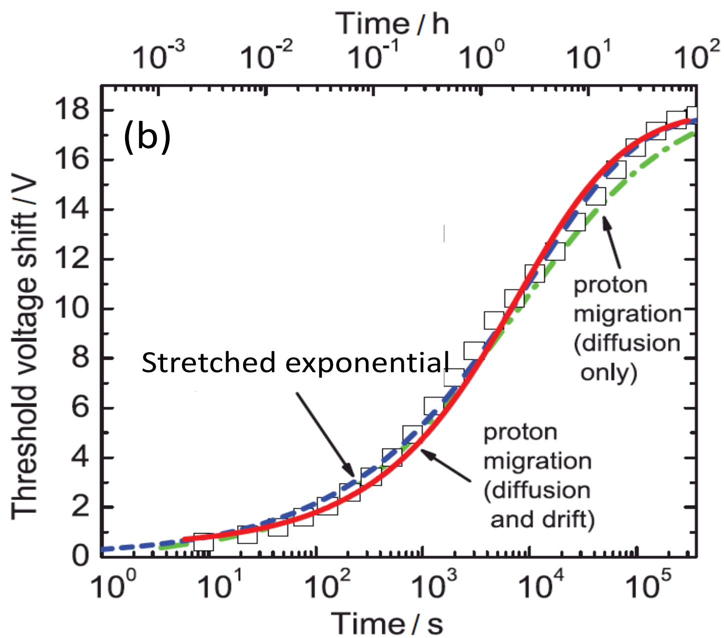




Example: Poly(triarylamine)

The voltage drift time constant:

- Follows the stretched exponential
- Is thermally activated with E_T = 0.6 eV



Threshold voltage is fit assuming proton diffusion and drift in the field under the gate

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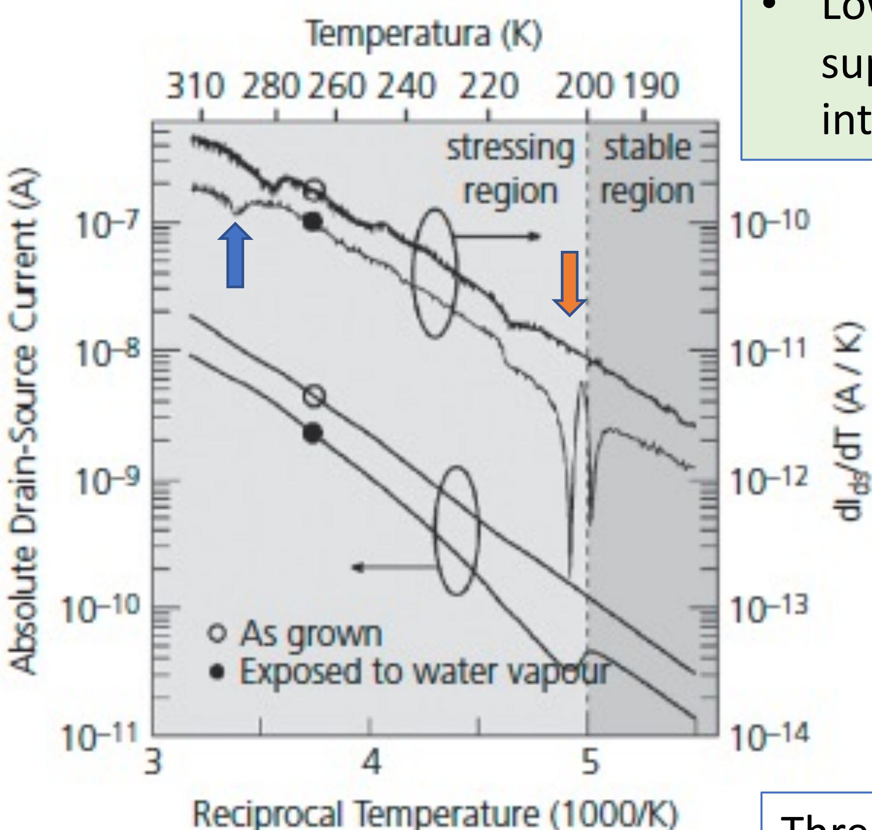
Bobbert et al, Adv. Mater. 24, 1146 (2012)

Evidence for H_2O at the Insulator Interface

- Change in drain current exposed to water shows peaks near 0°C and 205°C
- Low temperature peak due to freezing of supercooled H_2O clusters confined at the insulator interface

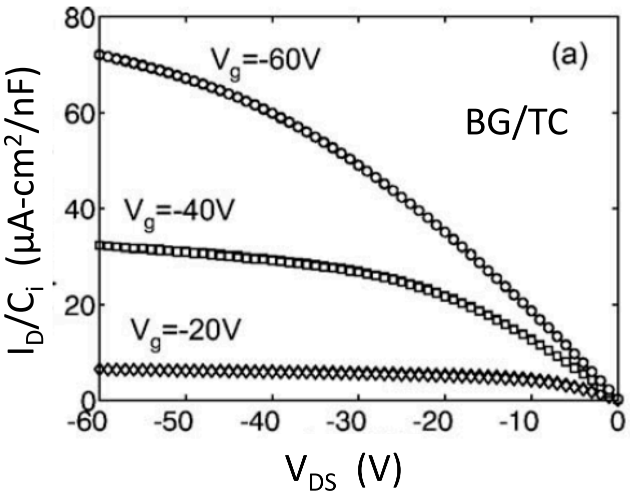


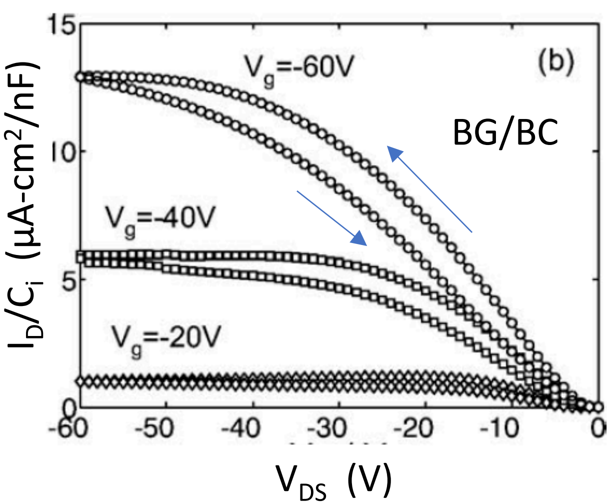
polyarylamine channel

Threshold drifts can be reduced by encapsulation
Similar stability improvements in packaged devices also observed for OLEDs and OPVs

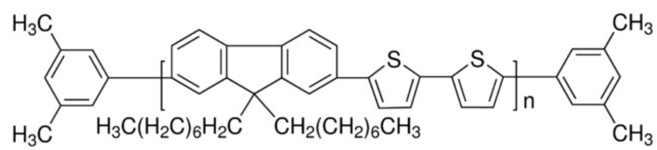
Gomes et al. Appl. Phys. Lett. 88, 082101 (2006)

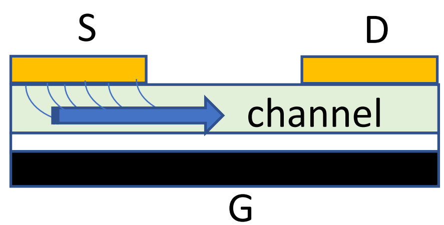
Hysteresis: Another failure mode



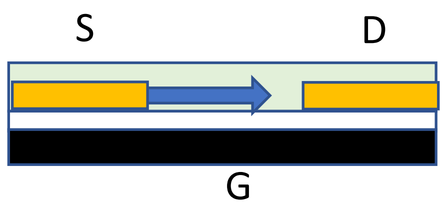


p-channel F8T2 transistors





BG/TC: Large contact area to channel
Current drawn from contact surface (arrow)



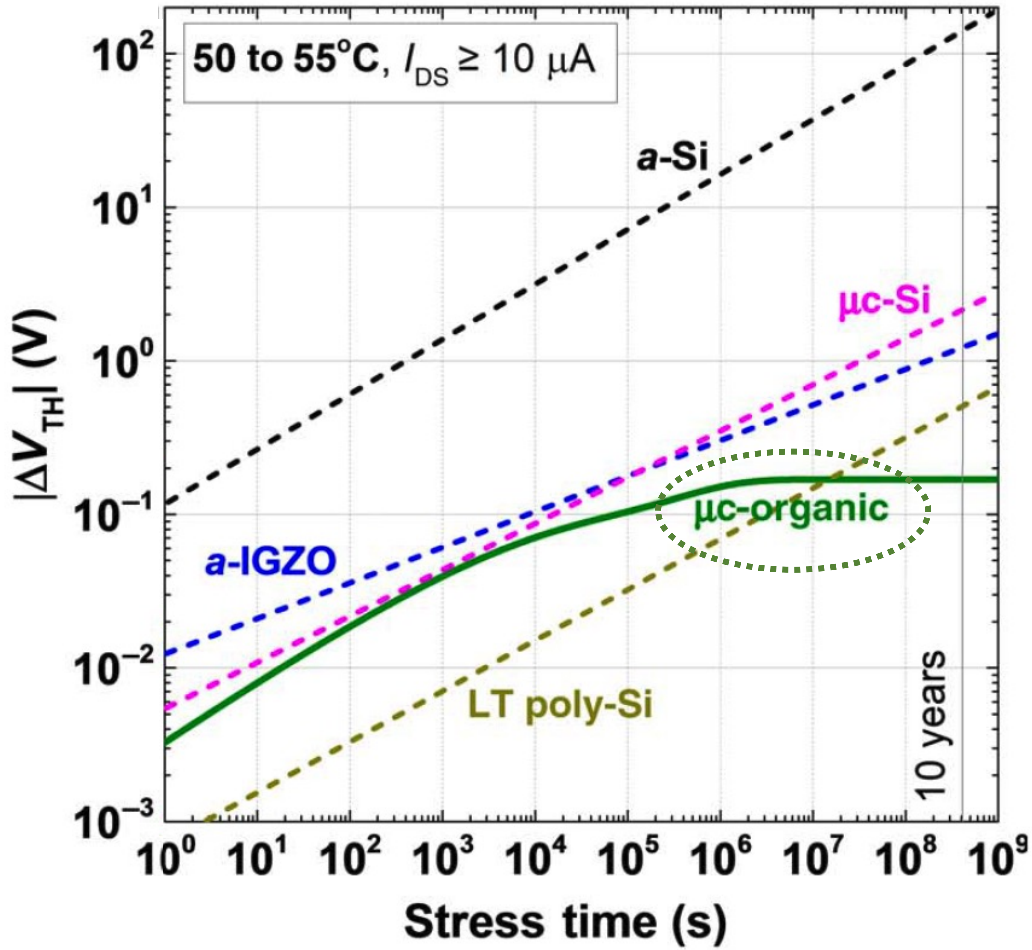
BG/BC: Small (edge) contact to channel
Current drawn from contact edge (arrow)

Drain contact trapping

Contact only via edge of the electrodes increases the current density, resulting in defect formation and charge trapping. This induces changes in V_T and I_{DS}, depending on sweep direction (arrows)

Richards & Sirringhaus Appl. Phys. Lett., 92, 023512 (2008)

Comparison of TFT Reliabilities



Jia, et al. Science Adv. 4, eaao1705, (2018)

Caveats (and there are many):

- Devices from different labs may be based on different standards and conditions
- Device selection not necessarily based on same characteristics
- Performance can vary over a wide range in any technology

Applications must exploit advantages, and cannot be vulnerable to disadvantages

To review….

- PROs
  - Flexible, conformable, ultralight
  - Can be made over very large areas
  - Suitable for large scale R2R manufacture

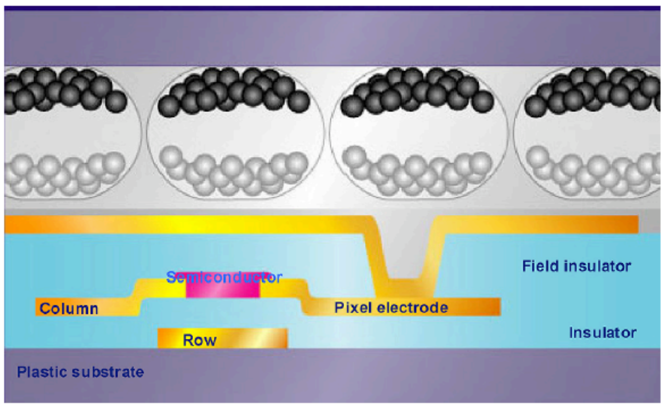
- CONs
  - Cannot source large currents
  - Characteristics drift over long periods in operation
  - Limited bandwidth (≤ 1 MHz in many cases)

Voltage driven display backplanes

- Electrophoretic displays

(a)

(b)

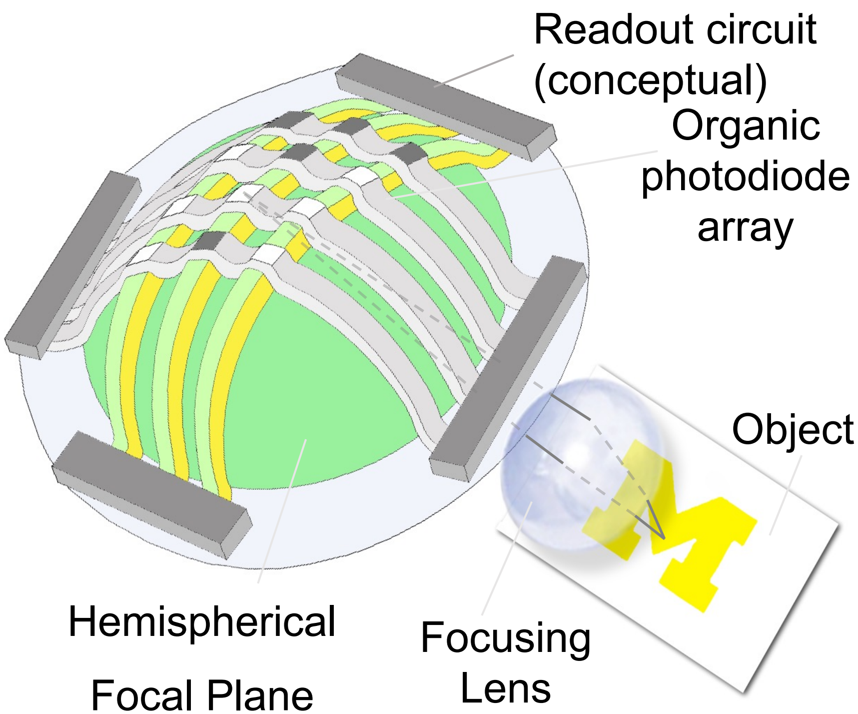


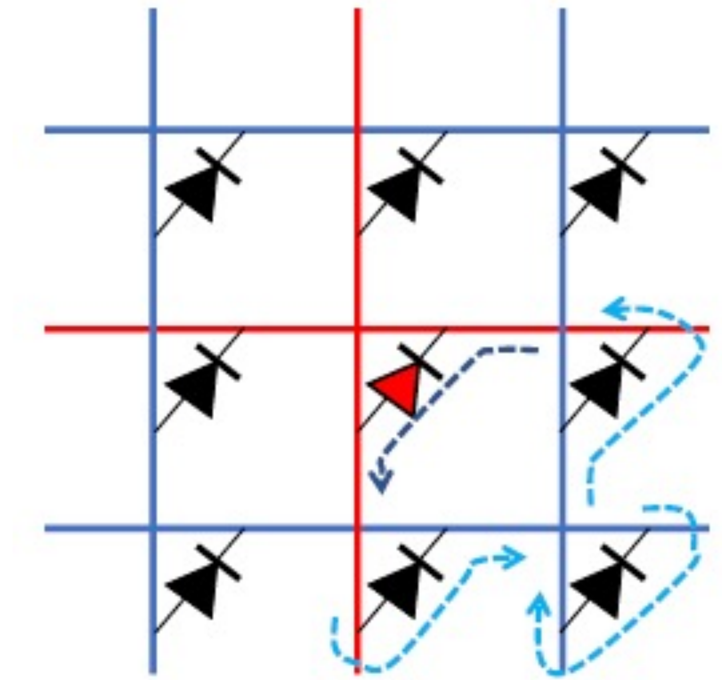
320 x 240 QVGA display
Display pixels are voltage (not current) driven

QVGA=quarter video graphics array

G. Gelinck *et al J. Soc. Info. Display,* **14**,113, 2006.

Optical Detector Arrays

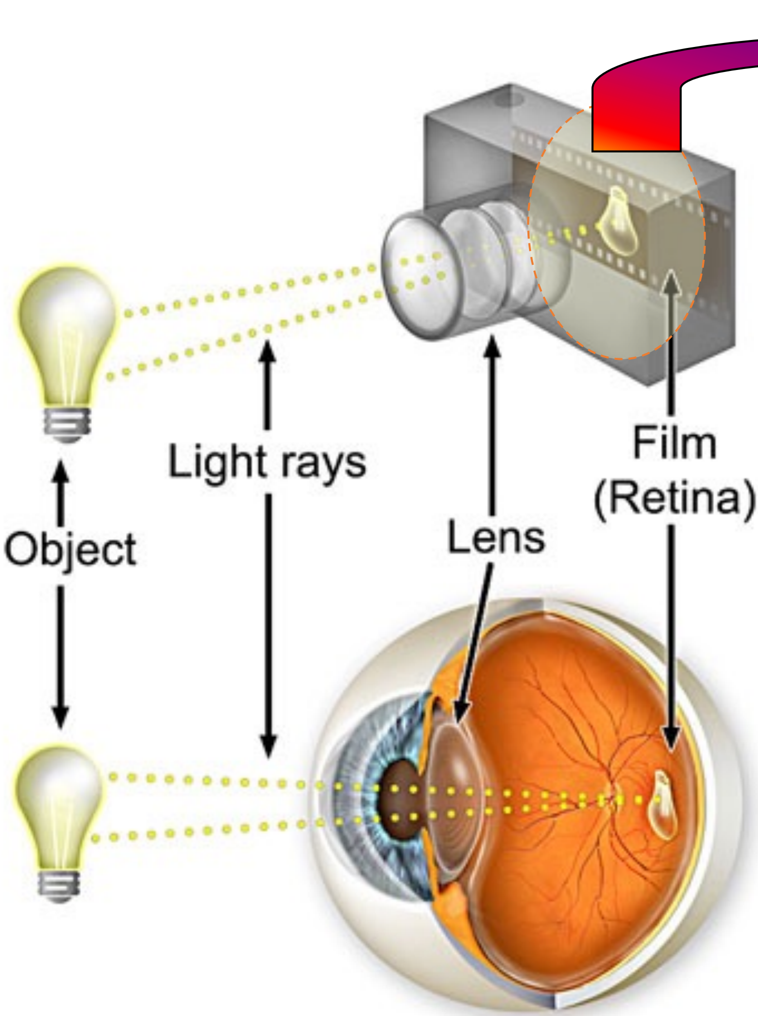




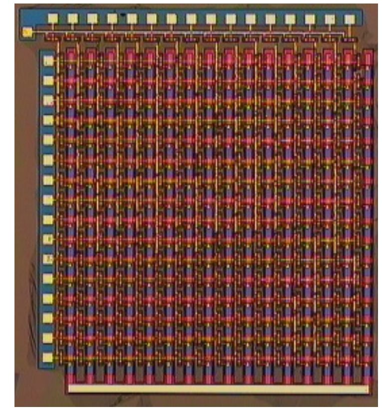
- Organics allow for fabrication on “non developable” surfaces: i.e. surfaces that cannot ordinarily be transformed from a plane without strain or distortion
- In Ch. 5 we showed that hemispherical focal plane arrays can be formed using the elastic properties of organics
- The FPA is in a passive matrix configuration
- “Sneak currents” (right) show that leakage from unaddressed detectors (black) can add to the photocurrent from the illuminated detector (red) in a passive matrix

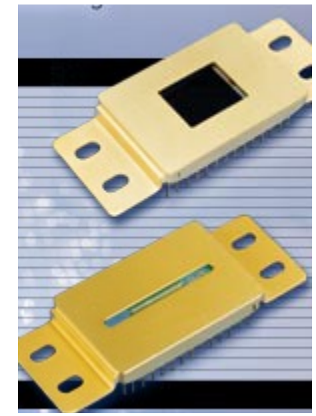
Xu et al. Organic Electron., 9, 1122 (2008)

Cameras vs. Eyes: A Comparison



Film has been replaced by flat arrays of detectors and transistors

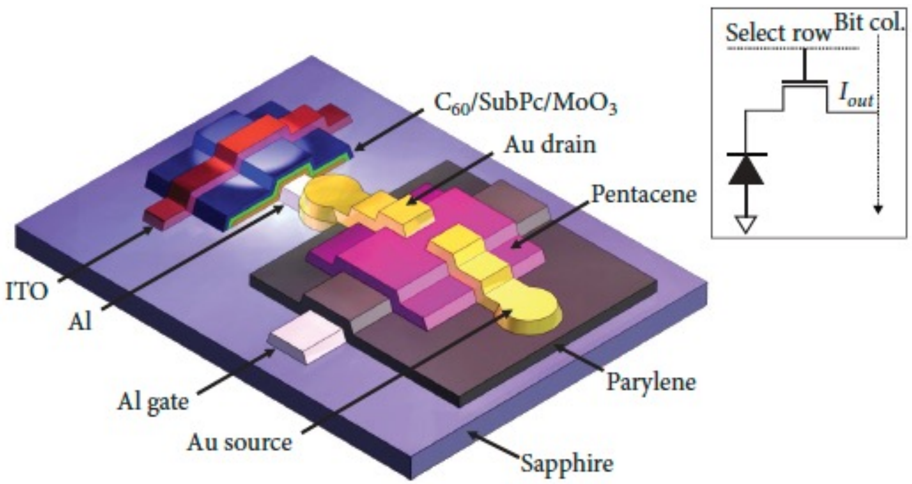


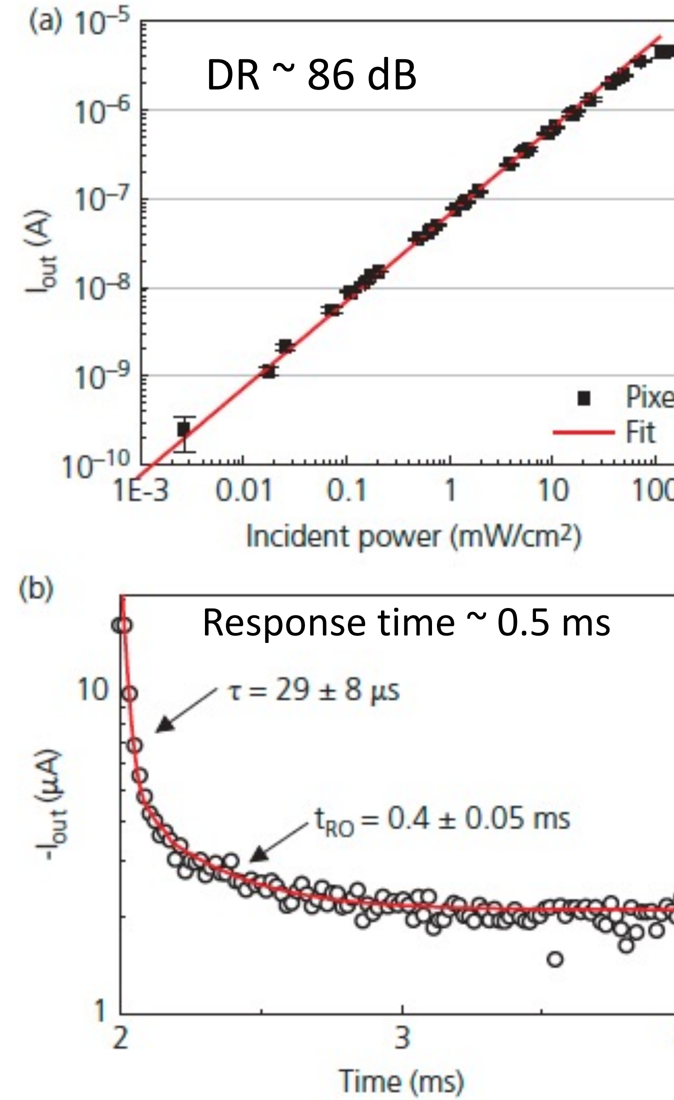


Function	Eye	Camera
Focal Plane	Curved	Flat
Lens	Single element	Multiple element
Weight	Light	Heavy
Field of View (FOV)	180 °	Narrow~160 ° (w. distortion)
Lens speed	Fast	Slow
Size	~ 1 cm^3	~200 cm^3
Weight	gm's	Kg's

But the eye detection system is on an approximately hemispherical surface

Transistor addressing circuits reduce sneak currents





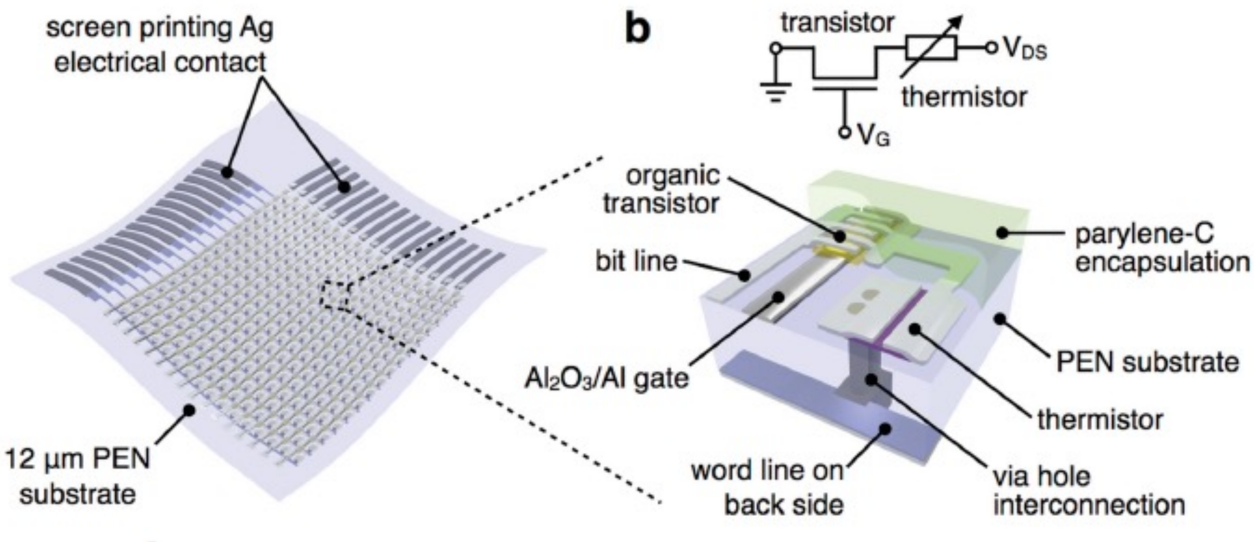
- One transistor address per pixel called passive pixel sensor
- Transistor used as switch to interrogate charge on photodiode in array
- Increases device dynamic range

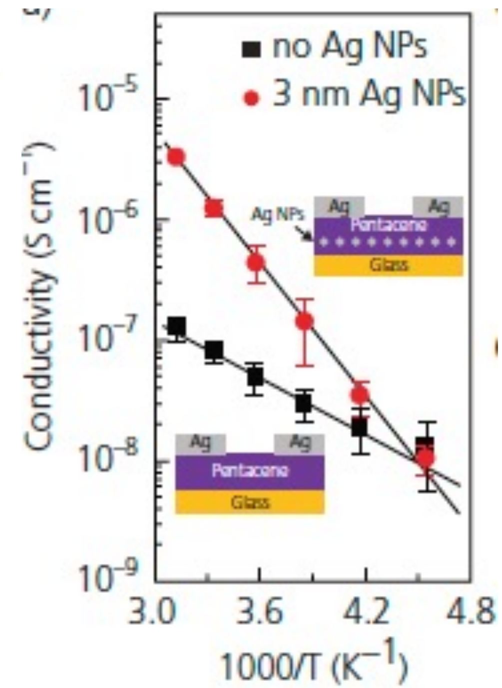
$$DR = 20log_{10}\left(\frac{I_{max}}{I_{min}}\right) \text{ [dB]}$$

I_{max} = max. photocurrent with < 1 dB distortion
I_{min} = min. detectable photocurrent with S/N = 1

Tong & Forrest, Organic Electron. 12, 1822 (2011)

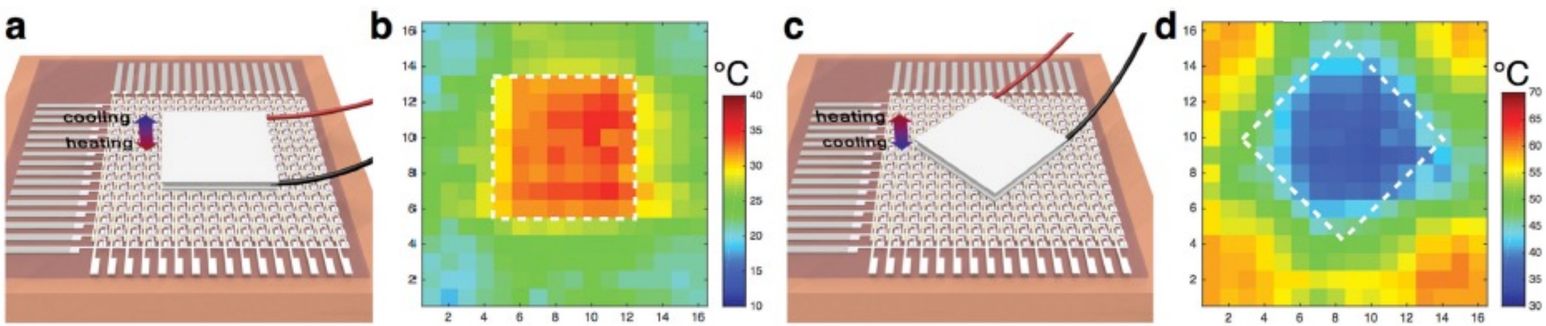
Thermal Position Sensing





Array used for detecting position of thermal source

Sensing element: channel resistance with a Ag NP layer



Ren, et al., Adv. Mater. 28, 4832 (2016)

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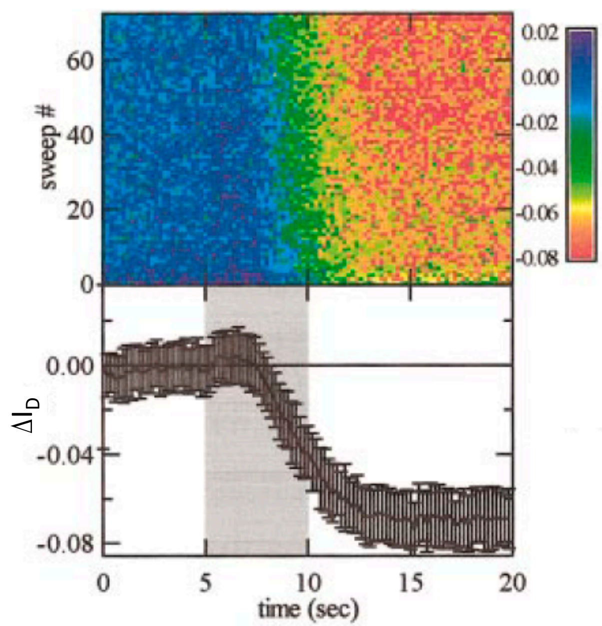
Chemical sensing

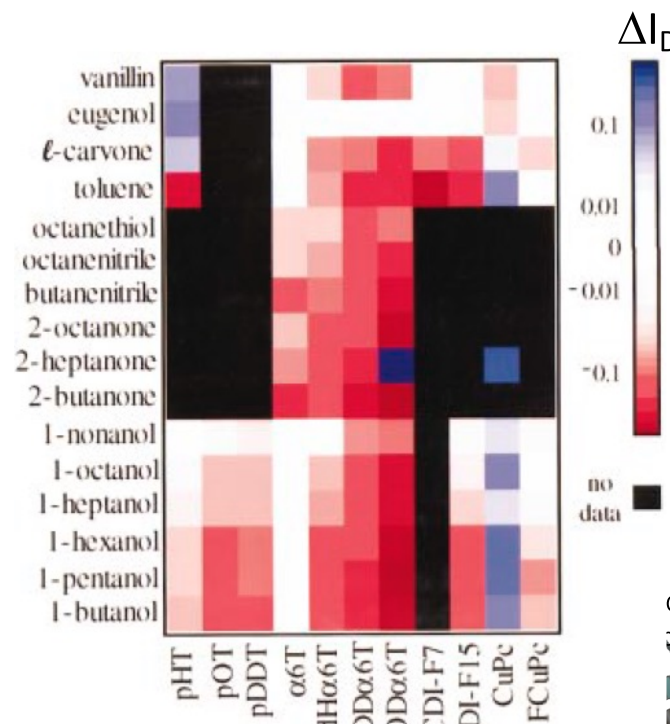
- OTFTs have demonstrated voltage drifts due to water.
- Are there other analytes that can be sensed?
- Sensor attributes
  - Fast
  - Sensitive to small doses
  - Reversible
  - <u>Specific</u>

α–6T transistor

Analyte: 1-hexanol
Exposure: 5 s
Recovery: 1 min

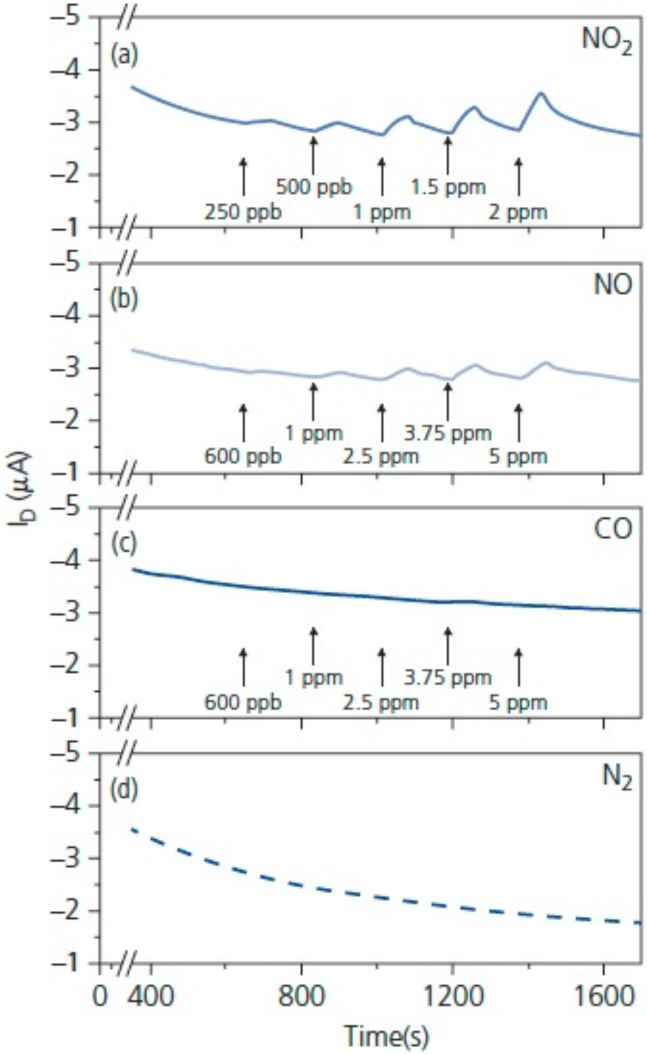


16 analytes
11 transistor channel mater.



B. Crone *et al.*, 78, 2229, (2001)

Analyte-Specific Sensors Using D_{3A} OTFT

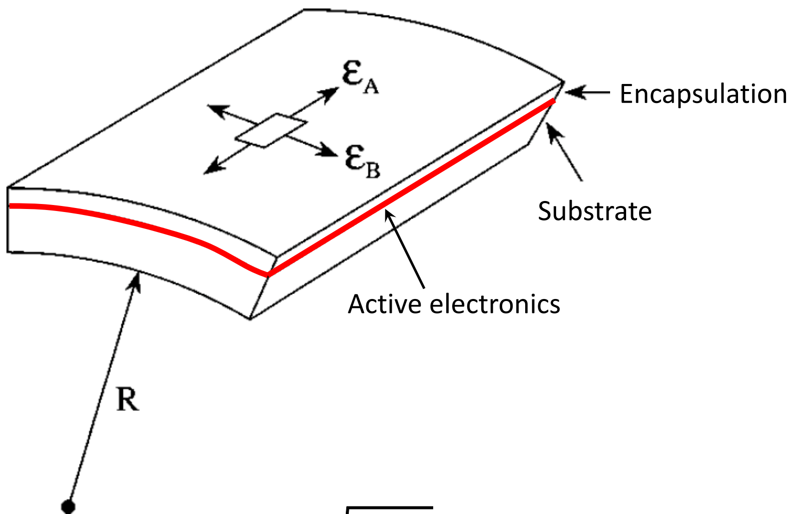


- Highly sensitive (ppm)
- Specific to NO_2 and NO
- N2 transient provides "no analyte" background

Marinelli et al., Sens. Actuators B Chem., 140, 445 (2009)

Bendable Electronics

Placing active electronics at the neutral strain point
⇒ minimal stress to circuits on bending even over sharp angles

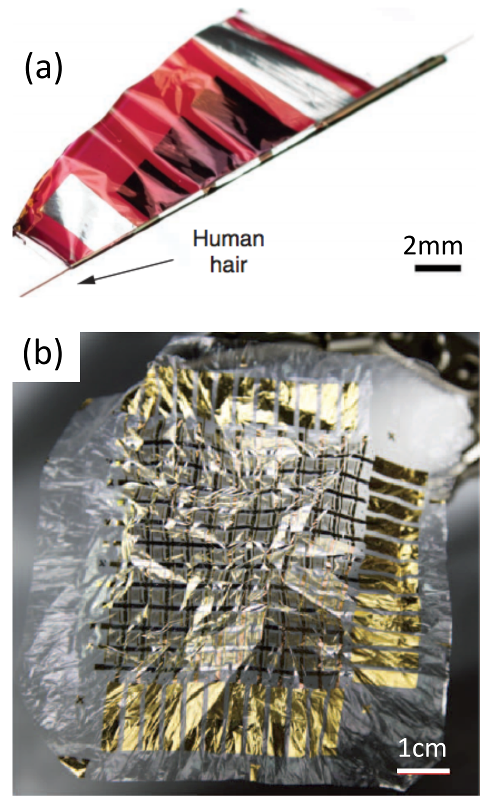


Neutral strain: $$\frac{d_{sub}}{d_e} = \sqrt{\frac{Y_e}{Y_{sub}}}$$

Y = Young's modulus (measure of material stiffness)

$$Y = \frac{FL_0}{A\Delta L}$$

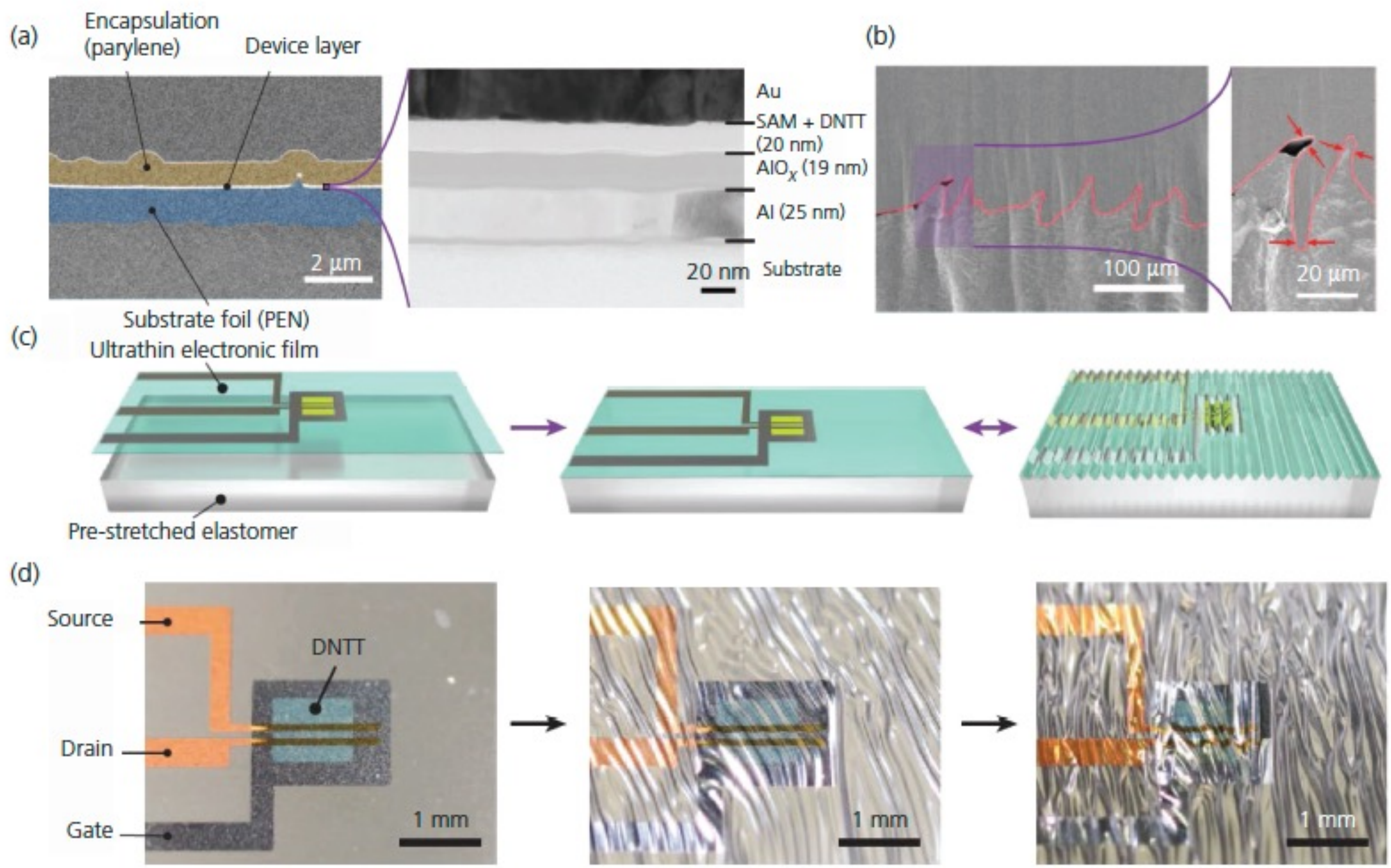
- F = force to extend solid
- L_0 = original length
- ΔL = length change
- A = cross sectional area perpendicular to F



12x12 array of tactile pixels

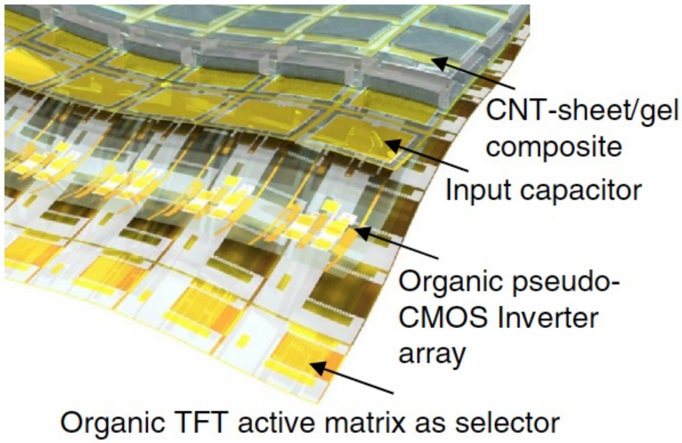
Kaltenbrunner et al. Nat. Commun.3, 770 (2012); Nature 499, 458 (2013)

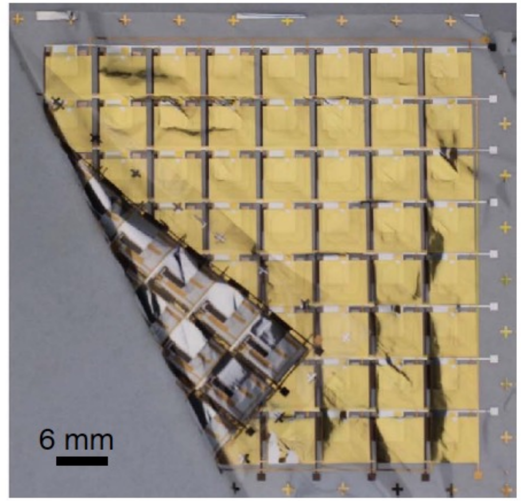
Strain can be Built into the Substrate

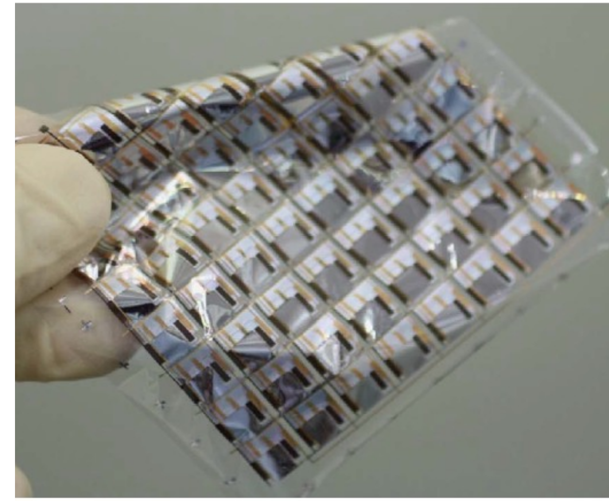


Kaltenbrunner et al. Nature 499, 458 (2013)

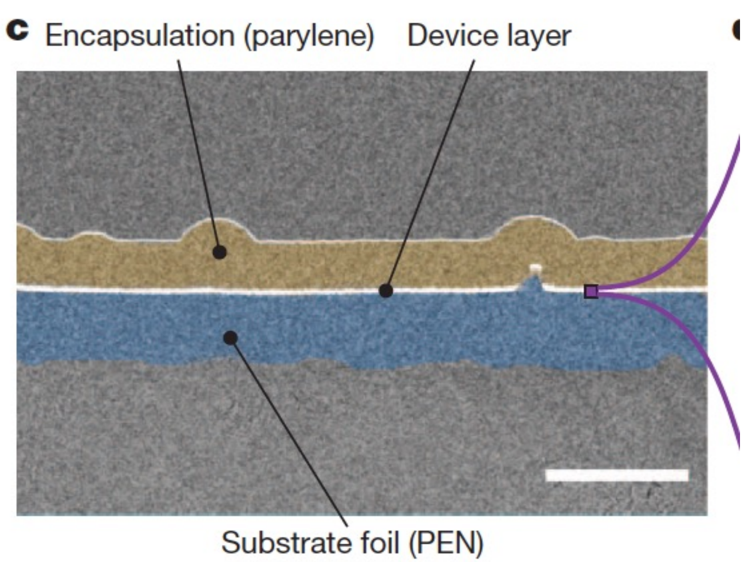
"Imperceptible" Electronics

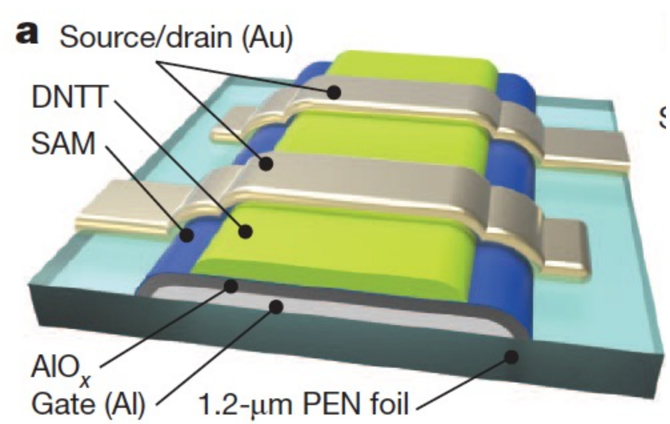






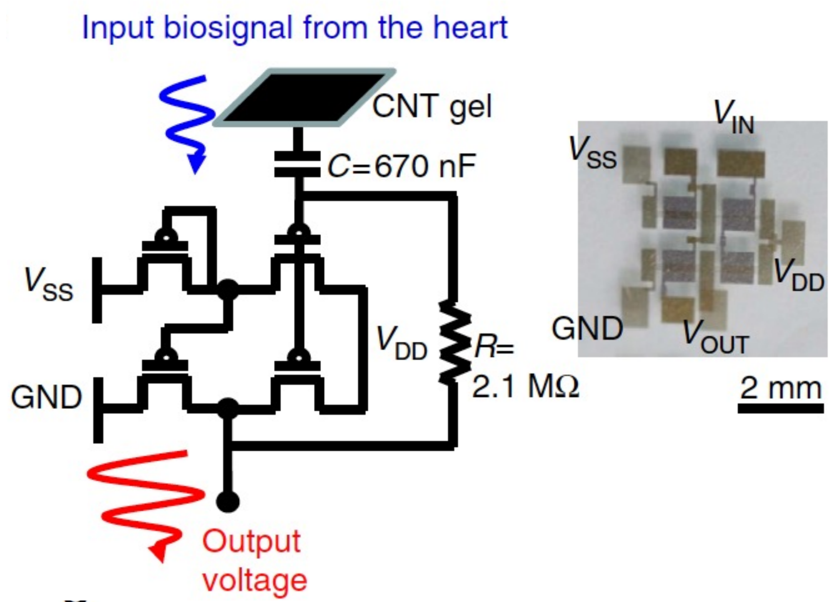
Substrates are 1 µm thick!

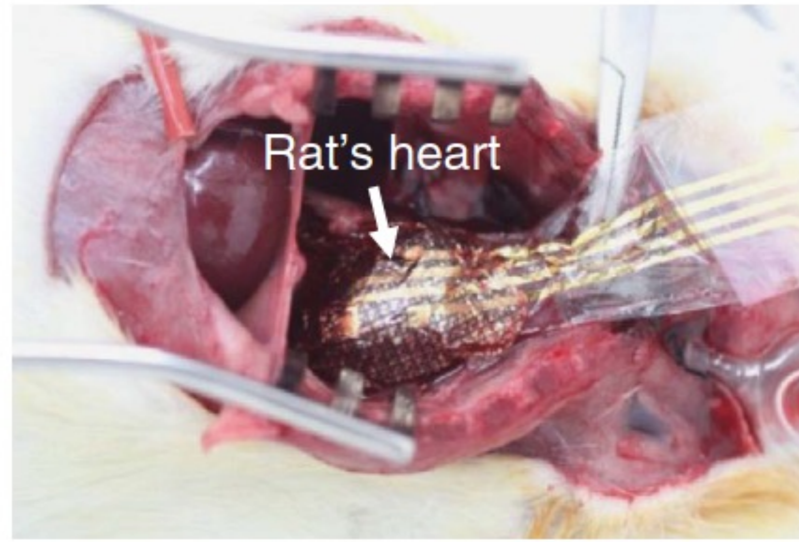


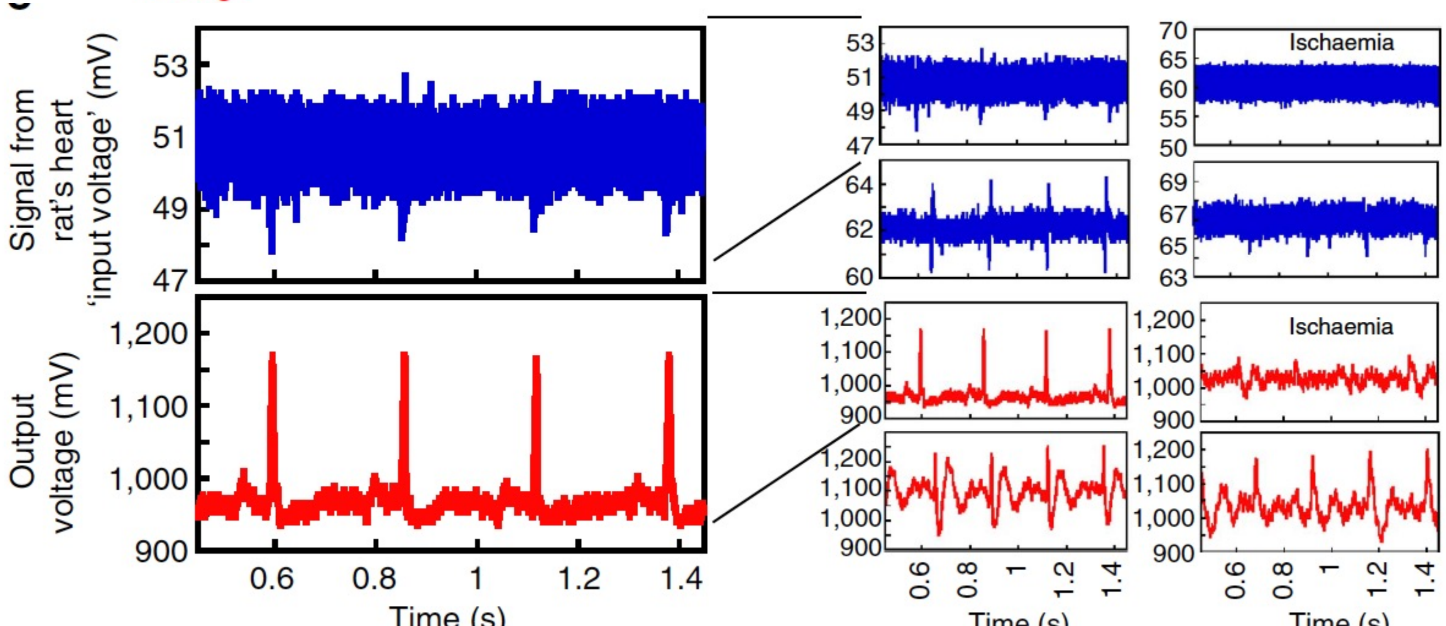


Kaltenbrunner, et al., *Nature*, **499**, 458 (2013).

In Vivo Cardiac Monitoring

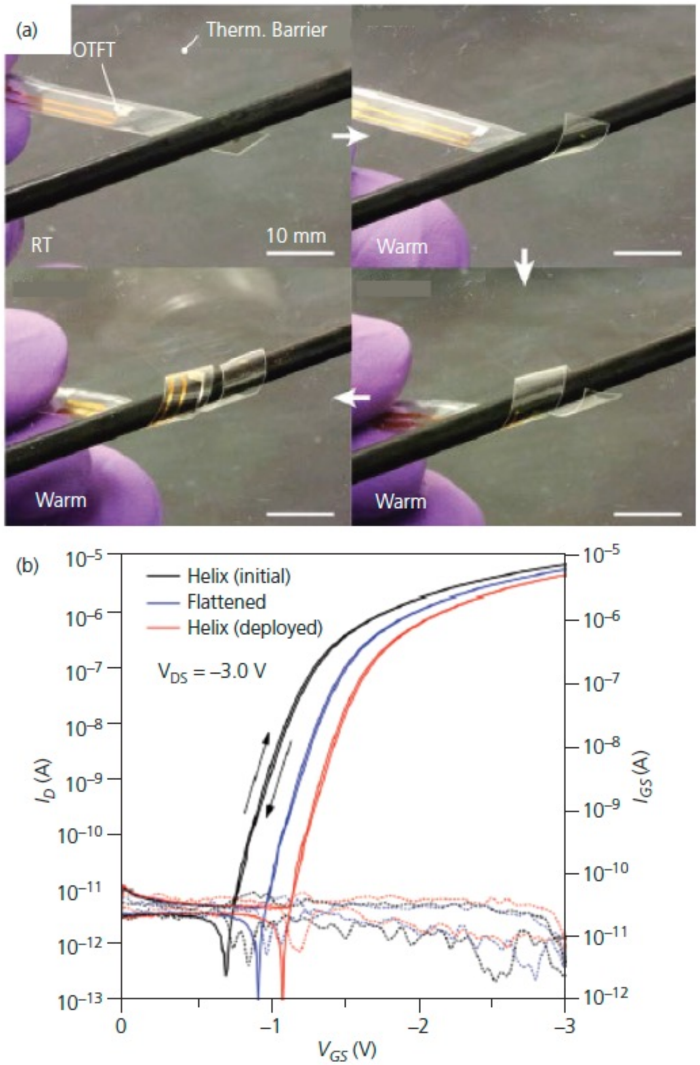


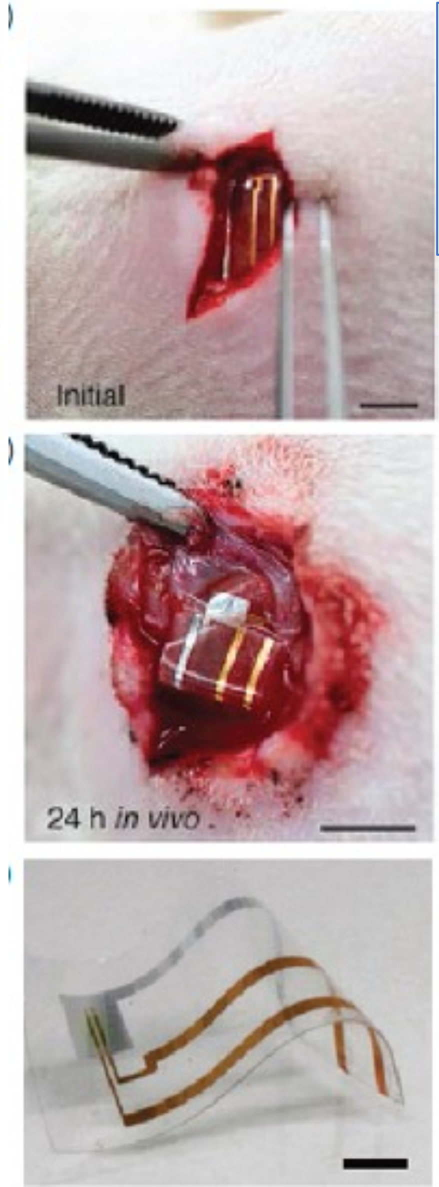




Sekitani, et al. *Nat. Comm*. DOI: 10.1038/ncomms11425 (2016)

Shape memory polymers





Shape memory: a deformed material “remembers” a previous configuration once a stimulus (e.g. temperature) is removed

- This property can be used to shape a circuit to conform to its surroundings (e.g. an organ or other structure)
- Often comprises a stressed bilayer
- In this example, the SMP is shaped to fit a wound without significant degradation of OTFT properties

Reeder et al., Adv. Mater. 26, 4967 (2014)

What we learned

- OTFTs have made extraordinary progress since their first demonstration in 1986
- Their properties can be modified through chemical design
- Morphology is key to high performance
- Very small gate transistors are common in BG/TC configurations
- Very large circuits demonstrated (100’s of transistors)
- Reliability depends on exposure to contaminants
- Most promising applications in sensing and medicine
- But….there is no “killer app” yet identified that can drive this technology to a commercial success